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Final Report

Observational studies of the coupled ocean-atmosphere system
using instrumented aircraft

Award ONR, N00014-90-J-1265

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AUGUST, 1996

1. Introduction

The purpose of this award was to provide graduate education in conjunction with two major field programs; the first to investigate the formation, development, and break up of stratocumulus clouds and the structure of extra-tropical marine boundary layer; and the second to investigate air-sea interactions over the tropical Pacific Ocean.

2. Background

The first study was based on aircraft data collected during the Atlantic Stratocumulus Transformation Experiment (ASTEX) in the Azores, augmented by aircraft measurements made in the vicinity of Britain and along the California coast. The second study, referred to as the Tropical Ocean Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment (TOGA COARE), was developed, in part, to investigate the processes that control the surface fluxes of heat, moisture and momentum over the warmest water in the Pacific, in a region of intermittent but intense atmospheric convection. Data collection and analysis was supported by the Marine Meteorology Program at ONR.

3. Results

Two students were selected to participate in this program. The first student completed his Ph.D in February 1996 and currently has a post-doctoral position at Scripps. The second student will complete and defend her thesis in November and will take up a post-doctoral position at the University of Washington in January 1997.

3.1 The development of a smooth particle hydrodynamic model and application to ASTEX

Dr. Peter Norris used the data collected during ASTEX to develop a smooth particle hydrodynamic model of the marine boundary layer. Most existing numerical solutions in computational fluid dynamics use the widely studied Eulerian approach, that is, prognosis of field variables at fixed locations within the domain. By contrast, smoothed particle hydrodynamics (SPH) is a Lagrangian technique, that is, it makes prognosis at positions which follow fluid elements within the domain. The technique was designed to deal with the unbounded simulations required in astrophysics, but finds increasing application in a variety of problems, ranging from high speed metallic impact to wave generation. Lagrangian methods require that the equations of motion be evaluated at a set of disordered points representing small fluid elements. The advective terms, which are difficult to evaluate in an Eulerian framework due to inherent non-linearity, are simply evaluated in a Lagrangian framework, because the prognosis positions are, by definition, advected with the local fluid velocity. This makes the method very amenable to other parcel processes, such as cloud microphysics, for example. Non-local processes, however, such as those involving the calculation of field gradients, are not so trivial. These gradients are estimated by first interpolating from the disordered fluid element positions and then using the gradients of the interpolation. In SPH, the fluid is divided into a large

but finite number of elements, which are localized as so-called "particles". Interpolation is then accomplished using a local weighting function, called the kernel, which distributes the properties of the fluid about the disordered positions of these particles. The kernel has some small finite range, which implies that the properties of a given particle are only affected by those other particles, called "neighbors", which fall within a certain range of the particle in question. We have applied the SPH method to the atmosphere, with a view to performing improved simulations of the cloud-topped marine boundary layer (CTMBL). The first part of our work involved designing a code to model the SPH equations for a stratified geophysical fluid. This involves a basic time-stepping routine for the compressible Navier-Stokes equations, a special design to allow efficient collection of near-neighbor particles, and a system for correctly initializing particle positions. In addition, we devised a new type of boundary condition to handle particle-wall interactions within a stratified fluid. The code has been written for operation on parallel machines, and an initial series of test runs (sound propagation, viscous diffusion, and buoyancy oscillations) indicate the method to be robust and accurate.

3.2 The atmospheric boundary layer over the central and western equatorial Pacific

Ms. Yolande Serra, who will defend her thesis in November 1996, successfully applied aircraft and buoy observations collected during the Coupled Ocean-Atmosphere Response Experiment (COARE) to develop a comprehensive understanding of the structure and evolution of the tropical marine boundary layer.

The Coupled Ocean-Atmosphere Response Experiment, within the Tropical Ocean-Global Atmosphere (TOGA) program, was developed to improve our understanding of the role of warm water regions on the ocean-atmosphere climate system. One of the primary goals of TOGA COARE is to describe and understand the principal processes responsible for the coupling of the ocean and the atmosphere in the western Pacific warm pool system. To address this and the other COARE objectives, aircraft data were collected between November 1992 and February 1993 in the western Pacific. These measurements were extended in March 1993 to the central Pacific as part of the Central Equatorial Pacific Experiment (CEPEX). A subset of the aircraft data was used to compare and contrast these regions and provide some insight into the coupling of the atmosphere to the ocean in regions of light winds and high humidity, and near deep organized convection. The data were obtained by the NCAR Electra, one of the principal platforms in COARE and CEPEX capable of direct turbulence flux measurements. Comparison of the aircraft data with long time series measurements from the IMET buoy, located at 1.75 °S and 156 °W, showed generally very good agreement, enabling us to develop a comprehensive data set that combined temporally and spatially well-determined measurements.

We used local surface layer similarity to highlight the variation of the surface fluxes as a function of the convective regimes. It was convenient to consider three categories: forced convection, free convection, and a transition region, which is a mixture of free and forced convection. While the prevailing winds in COARE were light (< 3 m s^{-1}) we observed a wide range of convective conditions. Free convection (*i.e.*, $\zeta < -5$), where

$\zeta = z_i / L$, z_i is the boundary layer height and L is the Obukhov length scale, resulted in a latent heat flux that was independent of ζ with a magnitude of about 60 W m^{-2}. In contrast, forced convection ($\zeta > -0.5$) resulted in scalar heat fluxes that were nearly linearly dependent on wind speed, decreasing to zero in light winds. This highlighted the importance of considering free convection in the parameterization of the surface fluxes and the likelihood of large errors if the effects of the buoyancy flux on the vertical velocity variance in light winds was not considered.

While the temperature of the warm pool region in COARE was found to be largely independent of local conditions measured by the aircraft, we observe that the warmest temperatures (> 30 °C) coincide exclusively with the lightest winds, which highlights the importance of wind-driven mixing in determining the thermal structure of the upper ocean.

4. Publications

4.1 Reviewed Papers

Serra, Y.L., D. P. Rogers, D. E. Hagan, C. A. Friehe, R. Grossman, R. A. Weller, and S. Anderson, 1995: Surface fluxes over the central equatorial and western warm pool of the Pacific Ocean. *J. Geophys. Res.*, Accepted for publication.

Rogers, D.P., X. Yang, P.M. Norris, D.W. Johnson, G. Martin, C. A. Friehe and B.W. Berger, 1995: Diurnal evolution of the cloud-topped marine boundary layer: Part I. Nocturnal stratocumulus development. *J. Atmos. Sci.*, 52 (16), 2953-2966.

Yang, X., D.P. Rogers, P.M. Norris, 1995: Diurnal evolution of the cloud-topped marine boundary layer: Part II. Simulation of the nighttime boundary layer. *J. Atmos. Sci.*, Accepted for publication.

4.2 Abstracts and Reports

Rogers, D.P., P.M. Norris, C.A. Friehe, B.W. Berger, D.W. Johnson, G.M. Martin and J.P. Taylor, 1993: Intercomparison of Aircraft Measurements of the Turbulence Properties of the Marine Atmospheric Boundary-Layer. *EOS*, 74, Supplement, 77.

Serra, Y.L. and D.P. Rogers, 1993: The Effect of Convection on Surface Heat Fluxes in the Western Tropical Pacific. *EOS*, **74**, no. 43, 125.

Rogers, D.P. and P.M. Norris, 1994: Evolution of Marine Stratocumulus Clouds: Analysis of ASTEX data. Preprints of the 8th Symposium on Atmospheric Radiation, American Meteorological Society, 243-245.

Yang, X., D.P. Rogers, P.M. Norris, D.W. Johnson, and G. Martin, "Stratocumulus Cloud Evolution". Preprints of the Second International Conference on Air-Sea

Interaction and on Meteorology and Oceanography of the Coastal Zone, American Meteorological Society, 74-75, 1994.

Norris, P.M. and D.P. Rogers, "Radiatively-driven Convection in the Marine Stratocumulus Clouds: Numerical Modeling". Preprints of the Second International Conference on Air-Sea Interaction and on Meteorology andOceanography of the Coastal Zone, American Meteorological Society, 64-65, 1994.

Rogers, D. P., Y. L. Serra et al., 1995. Mean structure and surface fluxes in TOGA COARE. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

Serra, Y. L. and D. P. Rogers, 1995. Comparison of enhanced surface fluxes and ocean mixing in determining sea surface temperatures. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.